



WEED MANAGEMENT IN SHORT ROTATION POPLAR AND HERBACEOUS PERENNIAL CROPS GROWN FOR BIOFUEL PRODUCTION

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Abstract—Weed management is a key element of any crop production system. Weeds are a particular problem in the production of short rotation woody and perennial herbaceous biomass crops due to the shortage of registered herbicides and integrated weed management systems. Herbicides will be an important component of weed management of biomass crops. However, producers should take a broader view of weeds and incorporate all available weed management tactics in these production systems. In both short rotation poplar and herbaceous perennial crops, weed control during the establishment period is most critical. New plantings of these species grow very slowly and do not compete well with weeds until a canopy develops. Effective weed control can double the growth of short rotation poplar crops and affect the variability of the resulting stand. In crops like switchgrass, uncontrolled weeds during establishment can result in stand failure. Cultural practices such as site preparation, using weed-free seed, fallowing, selecting the proper planting dates, companion crops and controlling weeds in previous crops must be combined with herbicides to develop integrated management systems. Weeds may also cause problems in established stands through competition with the biomass crop and by contaminating the product. Effective and economical weed management systems will be essential for the development of short rotation woody and herbaceous perennial biomass crop production systems. Published by Elsevier Science Ltd

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1. INTRODUCTION

Weeds are a unique group of plant species because of their ability to invade and often thrive in disturbed habitats despite extensive efforts to eliminate them. Weeds cause economic losses through direct reductions in crop yields, costs of control and reduced crop quality. Many definitions of weeds have been proposed, but the most useful may be “opportunistic species that follow human disturbance of the habitat”.¹ Weeds exist because production systems provide a place for them. Weeds in crop production fields reflect specific management practices.^{2–4} Crop production practices (e.g. tillage, planting dates, fertilization) exert selection pressure on weed communities and create niches that favor and disfavor various species.

Weeds are a major impediment to the development of alternative crops and cropping systems such as short rotation woody and herbaceous perennial biomass crops. Integrated weed management systems are essential for many biomass crops because herbicides are often not available for remedial action after weed populations have become established.

Weed management implies a shift away from reliance on control of existing weed problems and places greater emphasis on prevention of propagule production, reduction of weed emergence in a crop, and minimizing weed competition with the crop.⁵ Weed management emphasizes integration of techniques to anticipate and manage problems rather than reacting to them after they are present. Weed management does not eliminate the need for control nor does it advocate that the best control techniques be abandoned. The goal is to maximize crop production where

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appropriate and optimize grower profit by integrating preventive techniques, scientific knowledge and management skills. While additional knowledge is needed in all areas of weed management, the most important task of weed science is to increase knowledge of weed biology and ecology, creating a better understanding of weediness. This knowledge will lead to the use of appropriate management techniques rather than prophylactic approaches that produce short-term results, but may create or worsen long-term problems.

The purpose of this paper is to review the principles and practices of weed management in short-rotation woody and herbaceous perennial crops grown for biofuel production. The review focuses on the available information on weed control and identifies knowledge gaps and potential new approaches to weed management in biofuel crops. Information is also presented on optimum sampling methods to estimate early growth of short-rotation woody crops. Efficient estimation of woody crop growth is important because the relative value of weed management strategies cannot be judged apart from the impact of such strategies on crop productivity. Methods to identify optimum sampling strategies, and to explore the relation between sampling optima and weed management effectiveness are available but have not been applied to the early growth of short-rotation crops.

2. SHORT-ROTATION INTENSIVE HYBRID POPLAR PLANTATIONS

2.1. Introduction to weed control in hybrid poplar plantations

Establishing a successful hybrid poplar (*Populus* spp.) plantation requires effective weed control until tree canopy shade prevents weeds from growing.⁶ Failure to control weed competition will result in high tree mortality and a 50% or greater reduction in growth of surviving trees.⁷ Weed control begins with thorough site preparation and continues through year three or four. Control strategies include combinations of chemical and mechanical applications. These weed control techniques are described in the following sections. When properly established, plantations are ready for harvest in 6–10 years with yields

ranging from 6.7 to 13.5 metric ton of wood plus bark per ha per year.⁸

2.2. Site preparation

Hybrid poplars are typically planted on tilled or recently tilled agricultural land. Large agricultural tractors and equipment are used for site preparation. Implements include chisel and moldboard plows, field cultivators, discs, and harrows. Sod fields or fields infested with perennial weeds should be treated first with glyphosate [*N*-(phosphonomethyl)glycine] or similar herbicides before starting field operations. Herbicide application should be followed by deep fall plowing and disking. Plowing should be to a depth >25 cm to allow for the 25 cm cuttings that are planted the spring following site preparation. If the plantation site has been in a heavy sod such as fields converted to trees from perennial grass in the Conservation Reserve Program, special efforts including summer fallow may be required to gain control of weeds (Minnesota Department of Natural Resources, personal communication). If winter erosion is expected, fall seeding of an annual grass such as annual ryegrass (*Lolium multiflorum* Lam.) will protect the site. Weed problems are likely to occur from Canada thistle [*Cirsium arvense* (L.) Scop.] and annual and perennial grass species [e.g. *Setaria* spp. and quackgrass [*Elytrigia repens* (L.) Nevski]. No-tillage systems have been unsuccessful in establishing hybrid poplar plantations,⁹ especially in areas with a history of dense sods.

2.3. Plantation establishment

Hybrid poplars are normally planted between mid-April and early-June when the soil temperatures reach 10°C.⁸ Tree spacings range from 2.5 by 2.5 m to 3 × 3 m depending on the width of the available tending equipment. Narrower row spacings allow tree crowns to shade out weeds as early as year three or four. Wider spacings may require weed control through year five, six or longer. Hybrid poplars may be hand planted or machine planted using a variety of tree planting machines. Hand planting is generally preferred as the trees are accurately spaced allowing for cultivation in two directions (cross cultivation). This allows weeds to be mechanically controlled except for a small area next to the tree. In large, field scale operations, hand planted cuttings are more uniformly planted in

sites with heterogenous soils and site preparation. Control of planting depth and packing of cuttings is more difficult with machine planters.

2.4. First year weed control

During the first year weeds are controlled with a combination of herbicides and tillage equipment. Immediately after planting, overspray the plantation with the pre-emergent herbicide linuron [*N'*-(3,4-dichlorophenyl)-*N*-methoxy-*N*-methylurea] at the rate appropriate for the soil type using a standard agricultural sprayer. Weeds will be controlled for 4–6 weeks under normal rainfall patterns. Few other herbicides will effectively control weeds without damaging the poplars and fewer still are labeled for this use. If annual and perennial grasses invade the plantation during the first growing season, selective grass herbicides including sethoxydim {2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one} or fluazifop-butyl {(±)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoic acid} may be sprayed directly over the trees without damage. At this writing, no herbicide is labeled to control broadleaf weeds without damaging actively growing trees.

Broadleaf weeds may be removed during the first year using a variety of cultivation equipment, provided cultivation is shallow enough to protect the shallow poplar roots. Rotary hoes commonly used in corn (*Zea mays* L.) production will control weeds in trees < 30 cm tall. Conventional row crop cultivators set to tree row spacing and set to till < 5 cm deep will control weeds through the growing season. However, tool bars may need to be wrapped and adjusted to prevent tree injury late in the growing season. Plantations are typically cultivated three to five times during the first growing season depending on weed competition.

2.5. Year 2 and beyond

Once the trees are too tall to straddle with tractors and cultivation equipment, smaller between-row equipment must be used for plantation tending. Small old tractors, or newer compact tractors allow operation between rows spaced as close as 2.5 m. Narrow tillage equipment including light discs, rototillers and shovel type cultivators may be used to control weeds between rows mechani-

cally. This equipment can be used in plantations until canopies close. Frequency of mechanical cultivation is dependant on tree growth with the consequent shading of weeds, weed seed loads in the soil, and effectiveness of pre-emergent herbicides applied during the tree dormant seasons.

Typically, linuron is applied to unfrozen soil during the late fall or early spring when the trees are dormant. Sulfometuron {2-[[[(4,6-dimethyl-2-pyrimidinyl) amino]carbonyl]amino]sulfonyl]benzoic acid} also shows promise in dormant season application.¹⁰ A wide range of weeds are controlled by sulfometuron and in some cases control continues throughout the following growing season. The exception to this control is Canada thistle, which is not controlled by sulfometuron and increases in severity without competition from other weed species. Canada thistle has been effectively controlled with clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) during the growing season with no permanent damage to actively growing trees. Some leaf cupping and stem distortion occurred on young trees at the time of application, but later observations revealed no permanent damage to the trees. A wider range of herbicides need to be tested to determine their efficacy for weed control in poplar plantations, especially herbicides for post and pre-emergent control of broadleaf weeds.

2.6. Weed competition and tree growth and survival: a method to assess weed control

Effective weed management requires the integration of techniques to anticipate and manage problems. Such an integrated management strategy will require new kinds of knowledge about the newest crops, such as hybrid poplar. New knowledge will be required to apply weed management practices in site-dependent strategies that involve chemical and/or mechanical intervention only when such intervention is needed to support crop growth. For example, some sites may have weed populations that adversely affect crop growth. Such sites would be candidates for immediate intervention. In contrast, other sites may have similar weed populations while maintaining an acceptable rate of crop growth. Still other sites may have low weed populations that require little or no intervention. Central to any integrated management strategy will be efficient estimation of crop development on different sites and at

different times during the year. Guidelines for such estimations are not currently available.

Research was initiated in 1995 to determine optimum sampling guidelines for young hybrid poplar plantings. The study was conducted on two sites. Both sites were fall prepared in 1994 by application of glyphosate followed by plowing and disking. Sites were then planted with unrooted hybrid poplar cuttings in the spring of 1995. Site 1 was a well-drained site where mechanical and chemical weed control could be applied throughout the growing season. Site 2 was a poorly drained site where above-normal rainfall precluded intensive weed control because equipment could not move through the saturated soil. Four measurement plots were established on each site. Plots were pre-located by random coordinates to avoid visual bias. Tree height (cm), stem caliper (mm at a height of 10 cm), and number of leaves on the current terminal on each of 16 trees were determined within each plot. Measurements were done on 1 August 1995 and 6 September 1995. Data were subjected to analysis of variance and optimum two-stage sampling strategies were investigated according to the methods given by Cochran.¹¹

Hybrid poplar trees grew best on Site 1 where the most intensive weed control was practiced (Table 1). Trees at Site 1 increased height, caliper, and number of leaves from 1 August to 6 September by 73, 104 and 67%, respectively. In comparison, trees at Site 2 grew less during the same period (37, 45 and 34% for the same traits). It is certain that differences in growth can be attributed to multiple environmental factors besides differences in weed control. However, effective weed control, in the authors' opinion, was an important reason for the superior growth at Site 1. Thus, effective weed control can result in a significant increase in tree height growth by 1 August (77.5 cm vs 50.5 cm) and a nearly two-

fold advantage by the end of the growing season (134.0 cm vs 69.2 cm) (Table 1). Importantly, weed control practices should not be abandoned midway during the growing season because it has repeatedly been found that *ca* 50% of total seasonal growth during the first year occurs after 1 August.

Analysis of variance components within and between plots (Table 2) demonstrated that defining a sampling scheme that is optimum for all traits will be difficult, at all sites, during all times of the year, because of changes in the relative magnitude of variance among and within plots. For example, the relative magnitude of between vs within plot variance did not change greatly for tree height at Site 1 between the two sampling times. However, Site 1 and Site 2 differed strongly for the same trait, suggesting that different sampling strategies would be needed at the two sites. Notably, within plot variance was highest as a percent of total variance for all traits at Site 2 on 1 August where weed control was especially poor. This quantitative result is typical of the observations where ineffective weed control results in a lack of stand uniformity. Thus, the effectiveness of weed management affects not only tree growth (Table 1) but the variance structure within a plantation (Table 2) that defines how best to estimate tree growth.

Estimation of sampling optima given minimum cost and a standard error <10% of the mean suggested that the number of plots would range from 2 to 20 with the number of trees per plot ranging from 4 to 20 depending on trait, site and time. Dependence of sampling optima on local conditions, especially weed control effectiveness, suggests that a two-stage sampling scheme will be needed where preliminary estimates of between and within plot variance are obtained before a major investment in stand measurement.

Table 1. Mean tree height, stem calliper and number of leaves on the current terminal for hybrid poplars during their first year of growth from unrooted cuttings

	Site 1—good weed control		Site 2—poor weed control	
	1 August 1995	6 September 1995	1 August 1995	6 September 1995
Tree height (cm)	77.5 (9.8)	134.0 (16.9)	50.5 (4.6)	69.2 (8.3)
Stem caliper (mm)	6.8 (1.2)	13.9 (2.0)	4.0 (0.3)	5.8 (0.8)
Number of leaves	30.4 (3.1)	50.7 (3.2)	24.8 (1.0)	33.2 (3.6)

Site 1 was well drained allowing optimum mechanical and chemical weed control. Poor drainage at Site 2 precluded effective control. Standard deviations of the means are shown in parentheses.

Table 2. Variance (σ^2) between and within plots at two sites for tree height, stem caliper and number of leaves at two sampling times during the first growing season

	Site 1—good weed control				Site 2—poor weed control			
	1 August 1995		6 September 1995		1 August 1995		6 September 1995	
	σ^2	(%)	σ^2	(%)	σ^2	(%)	σ^2	(%)
<i>Tree height (cm)</i>								
Between plots	345	(45)	1025	(44)	68	(17)	226	(27)
Within plots	419	(55)	1301	(56)	341	(83)	617	(73)
<i>Stem caliper (mm)</i>								
Between plots	5.7	(50)	14.2	(36)	0.3	(16)	2.3	(33)
Within plots	5.6	(50)	25.1	(64)	1.6	(84)	4.7	(67)
<i>Number of leaves</i>								
Between plots	30	(26)	32	(22)	1.0	(3)	44	(34)
Within plots	85	(74)	115	(78)	35.6	(97)	87	(66)

3. HERBACEOUS PERENNIAL CROPS

3.1. Weeds and herbaceous perennial crops

Weeds reduce yields of herbaceous perennial species through competition for water, nutrients, light and space; and can lower the quality of forage and seed.^{12–15} Because seedlings of herbaceous perennial species grow slowly during the first several months after emergence, they are especially susceptible to weed competition. Stands may fail to become established because of uncontrolled weeds when weed pressure is intense. Seeding failures are costly because of the lost investment in seed, time, tillage, and land costs. Furthermore, seeding failures interfere with rotational sequences and product supply.

Perennial warm-season grasses often require two or more years after seeding before they can be harvested.¹⁶ This slowness and uncertainty of stand establishment deter land managers from seeding warm-season grasses. A major reason for this slow establishment is weed competition.¹⁷ Cool-season weeds are especially competitive with warm-season grass seedlings because of their rapid growth rates early in the spring.¹⁸

Besides direct competition, some weed species reduce establishment and yield through the production of toxins or growth inhibiting materials.¹⁹ Weed species shown to reduce growth of herbaceous perennial plants include quackgrass,²⁰ Canada thistle,²¹ and parasitic dodders (*Cuscuta* spp.).²² Weeds may also lower the quality of the biomass for energy production by reducing energy yield or causing drying or processing problems. Specific information on these issues does not appear to be available at this time, however, there are

examples of weeds reducing the quality of forage for animal consumption.²³ These same factors may affect forage quality for biomass production and processing.

3.2. Weeds and seedling establishment of perennial grass species

3.2.1. Weed problems. Weed interference limits establishment of perennial warm-season grasses from seed. Severe weed infestations often cause poor stand establishment or complete stand failure.^{17,24} In addition, the return on investment from perennial warm-season grass is usually delayed compared with annual crops because no income is generated during the year of establishment. Weed control may shorten the establishment phase allowing more rapid recovery of establishment costs and improving the economics of the production system. Weed control during the seeding year can also improve yields in the years after planting.^{17,25} For example, not controlling weeds during the establishment year reduced second year forage yields of big bluestem (*Andropogon gerardi* Vitman) and indiagrass [*Sorghastrum nutans* (L.) Nash] by 50 and 33%, respectively.²⁶

3.2.2. Herbicides. Herbicides are best used to supplement cultural weed management practices. This is especially important in perennial grass species because of the limited availability of herbicides for selective weed control. Herbicides may be broadly classified as toxic to either broadleaf or grass species, although there are exceptions where a specific herbicide will control certain species of both classifications. This gross selectivity is important in weed control in perennial grasses because most herbicides that control grass weeds are

also toxic to perennial grass plants, especially during the seedling stage of growth. Right now there are no herbicides registered that will selectively remove weedy grasses from seedling perennial grasses.

The information on herbicides given in this section is intended to provide general information on characteristics and uses of herbicides in the production of herbaceous perennial species grown for biomass. This information does not constitute a recommendation. These herbicides either are, have been, or may in the future be registered for use in the U.S.A. Herbicide labels are constantly changing. Thus, it is essential that product labels be consulted for specific uses.

Many herbicides have been evaluated for weed control during establishment of perennial grasses. Atrazine [6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine] has been the most effective, especially for establishment of switchgrass (*Panicum virgatum* L.). Unfortunately, atrazine is no longer registered for use in establishing perennial warm-season grasses in most states. While atrazine is not currently registered for the establishment of perennial warm-season grasses, it provides an excellent example of the utility of a broad-spectrum herbicide as an aid to seedling establishment. Atrazine suppresses many annual weed species growing with perennial warm-season grass species.^{17,27,28} There is wide tolerance for atrazine among perennial warm-season grasses, with switchgrass and big bluestem being two of the most tolerant species.

Atrazine is effective on a broad spectrum of broadleaf and grass weeds, however, it often does not control most annual warm-season grass weeds, including large crabgrass [*Digitaria sanguinalis* (L.) Scop.], fall panicum (*Panicum dichotomiflorum* Michx.), foxtail species (*Setaria* spp.), and barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.]. These annual grasses pose a serious threat to perennial warm-season grass establishment because of their similar growth habits.²⁹ Herbicides such as metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)-acetamide] and butylate [*S*-ethyl bis(2-methyl-propyl)carbamothioate] control annual warm-season grass weeds, but may injure perennial warm-season grass seedlings. Griffith *et al.*³⁰ tested the effectiveness of seed safeners to reduce herbicide injury to several perennial warm-season grass species. Big bluestem was

not injured by either butylate or metolachlor. Metolachlor did not injure switchgrass treated with naphthalic anhydride. Masters²⁹ concluded that metolachlor was a suitable replacement for atrazine to improve establishment of several species. However, yield and stand density were maximized when metolachlor and atrazine were used together.

Herbicides applied after crop and weed emergence can also be used to reduce weed competition in perennial warm-season grass seedlings. Summer annual broadleaf weeds are relatively easy to control with postemergence herbicides. Dicamba (3,6-dichloro-2-methoxybenzoic acid), MCPA [(4-chloro-2-methylphenoxy)acetic acid], and 2,4-D [(2,4-dichlorophenoxy)acetic acid] are registered for use in many perennial grasses and control a broad range of broadleaf weeds.³¹ However, there are few postemergence herbicides that have the potential to control summer annual grass weeds. Peters *et al.*²² evaluated several postemergence herbicides for control of barnyardgrass, green foxtail [*Setaria viridis* (L.) Beauv.], and large crabgrass in big bluestem and switchgrass. Big bluestem and switchgrass tolerated chlorsulfuron {2-chloro-*N*-[[[4-methoxy-6-methyl-1,3,5-triazin-2-yl]amino]carbonyl] benzenesulfonamide} and metsulfuron {2-[[[[4-methoxy-6-methyl-1,3,5-triazin-2-yl]amino]carbonyl]amino]sulfonyl]benzoic acid}, but these herbicides did not always control the summer annual grass weeds. Fenoxaprop {(±)-2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy] propanoic acid}, sethoxydim and haloxyfop {2-[4-[[3-chloro-5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoic acid} controlled annual grass weeds, but caused an unacceptable level of injury to big bluestem and switchgrass.

Imazethapyr{(±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid} is a postemergence herbicide that controls a wide spectrum of annual grass and broadleaf weeds in soybean [*Glycine max* (L.) Merr.] and peanut (*Arachis hypogaea* L.). Wilson³² evaluated the selectivity and weed control of imazethapyr in a range of perennial grasses. Application of imazethapyr 50 days after planting injured foliage of the perennial grasses. Imazethapyr application increased densities of blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex. Stued.] and little bluestem (*Andropogon scoparius* Michx.) 76 and 63%, respectively. Switchgrass

was more sensitive to foliar injury by imazethapyr, but a low rate still increased switchgrass density almost 50%. Weed biomass was reduced by imazethapyr and increasing the application rate further reduced weed biomass. However, increasing the imazethapyr rate also increased injury to perennial grasses, especially switchgrass.

Several herbicides have shown potential to provide selective weed control to aid the establishment of perennial warm-season grasses (Table 3). Additional research is needed to develop specific use practices for individual species and environments. While many herbicides may be effective, they may not be used unless they are registered for use in perennial grass establishment. Public sector research can provide evidence in support of herbicide labels, but the decision whether to pursue registration lies with herbicide manufacturers.

3.2.3. Preventive control. An effective component of weed management in biomass production is to prevent initial weed introduction. Using weed-free seed is the first step. Federal and state seed laws help protect growers from buying crop seed contaminated with weed seed through commercial channels. However, laws do not prevent growers from using their own seed or seed from a neighboring grower. If untested seed is to be used, growers can obtain a seed purity analysis from a public or private seed laboratory.

Cleaning equipment when moving from field to field is essential to reduce the transport of weed seed and plant parts of perennial weeds. For example, harvest equipment can carry

weed seed lodged within the machine.³⁴ Tillage equipment can transport seeds and vegetative parts of perennial weeds. Irrigation and flood water is also capable of moving weed propagules from one area to another.

3.2.4. Time of planting. Weed problems in new seedings of herbaceous perennial crops can be reduced or avoided by planting at a time of year when weed infestations are expected to be low and growing conditions are most favorable to the crop. Under natural rainfall conditions, spring seedings have the advantage of more dependable soil moisture supply than summer seedings in many areas of the U.S.A. In northern areas, spring seedings give plants time to reach sufficient maturity to survive the winter. Unfortunately, weed competition is usually most severe in the spring. Seeding dates need to be chosen to balance the desire to reduce weed pressures and to provide suitable conditions for crop establishment. Many annual weed species have a short period of emergence in the spring.³⁵ Therefore, delaying planting by as little as 7–14 days can greatly reduce weed competition with the crop.³⁶

In some situations, especially in southern areas, perennial crops may be planted in the summer or fall to avoid spring weed problems. Weed emergence may be decreased and crop growth faster following summer seeding giving the crop a competitive advantage over the weeds. However, there are risks involved with summer seeding. Soil moisture is often limiting during the summer and populations of insect pests are usually greater in the summer than

Table 3. Examples of herbicides evaluated for weed control during establishment of perennial warm-season grasses

Herbicide	Application time	Weed spectrum ^a	Crop injury potential ^b	Representative references
Glyphosate	Before planting	Nonselective	NA ^c	14
Paraquat	Before planting	Nonselective	NA	38
Atrazine	At planting	AB some AG	1–2	17,27,28
Butylate	At planting	AG	1–4	30,33
Metolachlor	At planting	AG some AB	1–3	29
Propazine	At planting	AB some AG	1–2	33
Chlorsulfuron	Postemergence	AB	1–2	22
Dicamba	Postemergence	AB	1	31
Fenoxaprop	Postemergence	AG	4–5	22
Imazethapyr	Postemergence	AB, AG	2–4	32
Haloxypol	Postemergence	AG	4–5	22
MCPA	Postemergence	AB	1	31
Metsulfuron	Postemergence	AB	1–2	22
Sethoxydim	Postemergence	AG	4–5	22
2,4-D	Postemergence	AB	1	31,33

^aAB, annual broadleaf species; AG, annual grass species.

^bInjury scale: 1, no significant injury to 5, significant plant death. Ranges often represent differential species response.

^cNA, not applied to planted or emergence crop.

other times of the year. Late seedings may not produce enough soil cover to protect the soil from erosion over the winter. The optimum planting date will vary by region, soil type and cropping practices. When selecting a planting date for herbaceous perennial crops, it is important to consider all environmental, soil and production factors.

3.2.5. Tillage and cropping practices. Tillage practices and cropping sequences can be effective in reducing weed seed content of the soil and weakening perennial weeds before the planting of a herbaceous perennial crop. Most of the annual weeds in a field are established from seed produced the previous year,³⁷ thus a high level of weed control in the years preceding establishment will reduce weed pressures. Delaying seeding to allow weed emergence before final seed bed preparation will improve weed control.¹⁴ Nonselective herbicides such as glyphosate or paraquat (1,1'-dimethyl-4,4'-bipyridinium ion) may also be used ahead of seeding to control emerged annual and perennial weeds followed by planting using stale seed bed³⁸ or conservation tillage methods.³⁹

3.2.6. Soil fertility. Any practice that promotes greater seedling growth and vigor will render the crop more competitive with weeds. Adjusting soil pH and nutrient to levels for optimum growth of individual species before planting will maximize competitiveness. Selective placement of fertilizers may also favor crop growth over weeds. For example, banding of fertilizer with the seed while planting promoted greater early growth of smooth brome grass (*Bromus inermis* L.) and alfalfa (*Medicago sativa* L.) and reduced yields of weeds.⁴⁰

3.2.7. Companion crops. The use of a companion crop is a method to manage competition during the establishment of a slow growing perennial crop. The goal is to replace an unmanageable weed population with a crop that can be managed and provide an economic return. The key to a successful companion crop system is using a companion crop that is competitive enough to suppress weed growth without competing excessively with the perennial crop. The best example of a companion crop system is the use of a small grain crop [usually oat (*Avena sativa* L.)] to aid in the establishment of alfalfa.¹⁴ In this system, the small grain and alfalfa are planted simultaneously early in the spring. The small grain emerges rapidly, protecting the soil from erosion and competing with weeds. Alfalfa seed-

lings become established under the small grain canopy. The small grain crop is harvested for forage or grain early in the summer, releasing alfalfa from competition.

Companion crop systems have not been developed for perennial warm-season grasses. The cool-season small grain crops used with alfalfa and other cool-season forage species are too competitive with perennial warm-season grasses. However, there may be other crops that are more compatible as companion crops for perennial warm-season grasses. Researchers at Iowa State University are evaluating corn as a companion crop for establishing switchgrass and big bluestem (K. J. Moore and J. R. George, unpublished data). Wide rows (>0.76 m) typically used for corn reduce its competitiveness, favoring establishment of the warm-season grasses. Wide rows also reduce weed suppression provided by the companion crop; however, the presence of corn may allow the use of herbicides registered for corn. Atrazine^{17,27} and imazethapyr³² are registered for use in corn and have displayed acceptable crop tolerance to several warm-season grass species, but currently are not registered for use with perennial grasses. If the warm-season grasses are not harvested during the seeding year, using these herbicides to control the weeds present in corn should be legal. Another advantage of this system is that the corn will provide income during the establishment year. Further research is needed to define cultural practices (e.g. corn populations, row spacings, warm-season grass seeding rates) needed to maximize yields of both the corn and warm-season grasses.

3.2.8. Clipping. Clipping done at the proper time is an effective method of weed control in new seedlings. Clipping height should be set to remove as much of the leaf tissue and lateral buds from which new growth initiates as possible. Annual grass weeds are not controlled as effectively as broadleaf species because regrowth is generated from crown buds near the soil surface below the point of clipping. Timeliness of clipping in relation to crop seedling development is important to avoid injury. Removing clippings from the field is also important if there is any indication that they will smother the crop seedlings.

3.3. Weeds in established stands

Crop competition can be very effective in keeping weeds out of established stands of

Table 4. Critical issues for weed management in biomass production systems

● Develop integrated weed management systems
— Establishment period
— Establishment stands
● Increase the availability of effective, economical and environmentally safe herbicides
● Increase the understanding of weed biology and ecology
— Effects of weeds on growth, yield and product quality
— Weed community dynamics
● Assess the potential environmental impacts of herbicide use on the fragile lands that may be used for production of biomass crops

herbaceous perennial crops. Mature stands that are properly managed will provide enough competition to control most annual weeds. Elements of a management program to maintain stands that are highly competitive with weeds include:

1. use of herbicides and other selective weed control agents;
2. proper fertility management;
3. insect and disease management;
4. proper harvest timing; and
5. avoiding winter injury.

Even under proper management, weeds may become established in healthy, dense stands of perennial grasses after harvest or during crop dormancy. Completely removing the above-ground portion of plants will change the ecology of the weed/crop system compared with native stands. For example, harvesting switchgrass three times per year reduced stand density and yield compared with a single harvest after 3 years.⁴¹ This reduction in stand vigor makes the stand more susceptible to weed invasions. Long-term research on weed population dynamics in established stands of switchgrass and other perennial warm-season grasses are needed to address this issue.

4. SUMMARY AND CONCLUSIONS

Weed management is a key element in the establishment and production of short rotation poplar and herbaceous perennial biomass crops. Weed control is especially important during establishment when weeds have a competitive advantage. There are currently few herbicides registered for use in most biomass crops. Therefore, cultural practices such as proper site preparation, weed-free seed, fallowing, proper planting date, timely tillage, reducing weed pressure in previous crops, clipping weeds and using companion crops are essential to the development of integrated weed man-

agement systems for hybrid poplar, perennial warm-season grasses and other biomass crops.

Weeds will also play a role in production systems following establishment, especially in warm-season perennial grasses. Based on experience in forage and pasture systems, intensive harvest of perennial warm-season grasses will make stands more vulnerable to weed invasions than natural stands. Therefore, weed management will be an important component of management throughout the life of a stand.

Significant challenges remain in weed management in short rotation woody and herbaceous perennial species grown for biomass production (Table 4). Cooperative efforts among public sector researchers, herbicide companies, producers and processors will be required to meet these challenges.

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